# FINAL REPORT

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### An Initial Investigation of the Performance of Soil Organic Carbon in Smallholder Regenerative Agriculture Trial Area: Case of North Sumatera and Jambi, Indonesia

PREPARED BY INRISE
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**PROGRESS REPORT**

# Menakar kontribusi petani swadaya dalam mitigasi perubahan iklim, melalui skema pertanian regenerative agriculture:

## *An Initial Investigation of the Performance of Soil Organic Carbon in Smallholder Regenerative Agriculture Trial Area: Case of North Sumatera and Jambi, Indonesia*


### *Executive Summary*

*Recently, palm oil smallholders have been introduced to low carbon practice. Farmers are expected to have awareness about the impacts of their farming practices to carbon stocks in soil. Regenerative agriculture may give a promise to advances environmental restoration and resilience through circular economy principles within oil palm landscapes. Central to this approach is the quantification of soil organic carbon (SOC) as a measurable indicator of emission reductions and ecosystem regeneration. This article aims to explore whether such introduction might contribute to develop alternative pathway for improving sustainability of smallholder palm oil production.*

*The study was conducted in the two study sites in Bandarejo Village, Bandar Masilam Sub District, North Sumatera, and Mekarsari Village, Rimbo Ulu Sub District, Tebo Regency, Jambi. The 20 x 20 m square sample plot was used, 12 plots in total were applied in the two study sites. This resulted in a total of 240 soil samples from the North Sumatra and Jambi sites, plus 12 samples for bulk density analysis. There were 48 composite samples for all locations, and further sent to the soil laboratory to perform a soil chemical (soil organic C) and soil physical (bulk density) analysis. Socio-economic data were collected using in-depth interviews and focus group discussion (FGD), in North Sumatera and Jambi sites respectively. In-depth interviews were taken place to get a deep understanding of smallholder palm oil plantation management both in transition of regenerative and conventional practices.*

*Insignificant impacts on SOC-related soil properties is highly related to insufficient organic application. Those organic applications were the trial practices dedicated by farmers, that is currently in the first and the second years. Although the increased SOC in this study ranged from 2–6%, it indicates a positive contribution to climate mitigation efforts. Conceivably, an increase of 1.35 to 2.35 tonne of SOC/ha contributes to emission reductions equivalent to 4.94 tonne of $CO_2$/ha to 8.62 tonne of $CO_2$/ha compare with and without regenerative agriculture.*

*Regenerative agriculture is then considered a promising strategy for improving SOC. However its widespread adoption is limited by several factors, among other: limited resources, including financial source, and weak institution in mainstreaming organic applications in the application of regenerative agriculture.*

*Finally, a couple of implications for smallholder regenerative agriculture to be considered, namely: the need on increasing technology adoption, access to organic materials, collaboration and networking, as well as developing an incentive and reward system. By implementing these improvements, smallholders can increase production and income, improve soil and environmental quality, and ultimately resulting in an improved smallholder regenerative agriculture framework.*


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## 1. Introduction

The governance landscape for palm oil sustainability has undergone sweeping transformation in the past two decades, shaped by transnational private initiatives, state regulatory responses, and new forms of hybrid governance (Schleifer et al., 2019; Dros et al., 2022). Early market-led certification standards, most notably the Roundtable on Sustainable Palm Oil (RSPO), emerged in the mid-2000s with support from industry, NGOs, and multilateral actors (Schleifer et al., 2019; de Man & German, 2017). RSPO set benchmarks for social and environmental practices, reaching over 20% of global palm oil production, but concerns about effectiveness and inclusivity remain (Hospes, 2014; Dros et al., 2022). Comparative analyses continue to highlight gaps in rigor and coverage among private standards, such as RSPO and ISCC (de Man & German, 2017).

The rise of state-backed certification regimes—including Indonesia Sustainable Palm Oil (ISPO) and Malaysian Sustainable Palm Oil (MSPO)—has signalled a reassertion of government authority over domestic sustainability governance (Glasbergen, 2018; Hadi et al., 2024). National schemes embed certification in law and local priorities, and both complement and compete with transnational standards (Hadi et al., 2024). Rigorous reviews demonstrate these differences shape enforcement, stakeholder inclusion, and adaptation to global demands (Glasbergen, 2018; de Man & German, 2017).

Most recently, the introduction of the European Union Deforestation Regulation (EUDR) marks a new regulatory turn, emphasizing geolocated traceability and direct supply chain mapping over reliance on third-party certification (Dros et al., 2022; Schleifer et al., 2019; Gilbert, 2024). EUDR regulation, effective 2024, requires plot-level evidence of deforestation-free production and places the onus of data submission and verification on producers and traders (Dros et al., 2022). This regulatory shift challenges both state and private certification systems, accelerating the search for robust, data-driven compliance structures (Gilbert, 2024).

Against this backdrop, non-state practitioners—NGOs, corporations, and researchers—have begun to articulate and pilot "beyond sustainability" frameworks that move beyond harm reduction toward ecological renewal and adaptive governance (WWF, 2023; Hairiah et al., 2022). Regenerative agriculture has emerged as a leading paradigm, incorporating restorative land management, biodiversity enhancement, and local co-benefit generation (Hairiah, et. al., 2022; WWF, 2023). Empirical studies demonstrate promising outcomes for soil health, climate resilience, and productivity, supported by private certification bodies and cross-sector partnerships (Hairiah, 2022). However, its application to smallholders still shows a lack of sufficient data and information to assess its effectiveness.

Several critical gaps are identified. First, longitudinal studies linking specific regenerative management interventions to measurable SOC change in smallholder oil palm systems in Indonesia are conspicuously absent. Most existing SOC research in the region is observational and cross-sectional, comparing land use types at a point in time rather than tracking dynamic responses to management change within a given land use category. Second, the literature on smallholder adoption of low carbon practices in palm oil contexts has not yet grappled adequately with the interaction between practice adoption and SOC outcomes. Even where farmers adopt recommended practices — such as EFB mulching, reduced tillage, or cover cropping — evidence of the corresponding SOC response in real-world smallholder settings, rather than controlled experiments, remains thin. Bridging this gap requires interdisciplinary research designs that combine agronomic monitoring with social science methods, enabling researchers to understand both the uptake and the ecological consequences of regenerative practice adoption simultaneously.

This paper critically examines the operationalization and diffusion of regenerative initiatives in the smallholder palm oil sector. It analyzes the evolving interplay among the sustainability experiments and climate mitigation benefits in reshaping sustainability governance, by asking two research questions, namely: (1) To what extent the role of regenerative agriculture in soil organic carbon enhancement, and (2) What are the socio-economic challenges in integrating regenerative agriculture for emission reduction on beyond sustainability perspective of smallholders' palm oil plantation management. The paper wants to analyze the opportunities given by the raising of regenerative agriculture concept in the initial phase of its implementation by the community and its socio-economic challenges.

## 2. Conceptual Framework

### 2.1. Smallholder Palm Oil Production: Scope, Challenges, and the Sustainability Imperative

Smallholder farmers — broadly defined as independent operators cultivating fewer than 25 hectares — account for approximately 40 percent of global palm oil production and a significantly higher share in countries such as Indonesia and Malaysia (Euler et al., 2017; Santika et al., 2019). Their economic contribution is substantial, yet the fragmented and often informal nature of smallholder operations makes them difficult to reach through standard certification and sustainability compliance frameworks. The Roundtable on Sustainable Palm Oil (RSPO), the dominant voluntary certification scheme, certifies only a small fraction of independent smallholders globally, owing to the high transaction costs of auditing, the technical complexity of standard requirements, and the limited organisational capacity of farmer groups (Jelsma et al., 2017; Hutabarat et al., 2018).

Research conducted in Jambi province illustrates the structural vulnerabilities of Indonesian smallholder systems. Euler et al. (2016) document yield gaps of up to 50 percent between smallholders and large estates, attributable to suboptimal agronomic practices, inadequate access to quality inputs, and limited technical support. Household income studies in Jambi and North Sumatra further reveal that while palm oil revenues have elevated living standards relative to alternative commodities, they have also deepened household exposure to volatile global commodity prices and exacerbated land inequality (Klasen et al., 2016; Nájera Espinosa et al., 2021). These structural constraints mean that sustainability interventions must simultaneously address productivity, economic viability, and environmental outcomes — a challenge sometimes described as the 'triple bottom line' dilemma in smallholder contexts (Lee et al., 2020).

Corporate stakeholders in global palm oil supply chains have responded to mounting pressure from consumers, investors, and regulators by embedding sustainability requirements into sourcing agreements and supplier development programs (Lambin et al., 2018). Increasingly, these programs extend beyond deforestation commitments to encompass positive environmental contributions, including carbon sequestration. Within this landscape, regenerative agriculture frameworks have gained traction as a potential bridge between corporate sustainability ambitions and the on-farm realities of smallholders.

### 2.2. Regenerative agriculture

Regenerative agriculture goes beyond “sustaining” ecosystems by promoting active restoration of soil health, biodiversity, and ecosystem services while supporting socio-economic resilience (Toh et al., 2022; WWF, 2023). This broadens the sustainability discourse to include ecological regeneration as a core outcome, addressing persistent challenges of land degradation and climate change mitigation that conventional certification schemes struggle to fully capture (Toh et al., 2022).

A notable theoretical underpinning often associated with regenerative agriculture is the concept of the circular economy. Circular economy principles emphasize resource efficiency, waste minimization, and closed-loop systems, aiming to decouple economic activity from resource depletion and environmental degradation (Geissdoerfer et al., 2017). In the palm oil context, circular economy strategies include recycling organic matter, optimizing nutrient cycles, reducing external chemical inputs, and valorizing waste products such as empty fruit bunches and palm kernel shells (Wijaya et al., 2020).

Integrating circular economy principles strengthens regenerative agriculture's capacity to reduce greenhouse gas emissions and promote system resilience by transforming linear production models into regenerative cycles (Toh et al., 2022). This approach fosters sustainable intensification aligned with climate-smart agriculture paradigms, facilitating emission reductions both directly—through enhanced soil carbon sequestration—and indirectly—by lowering energy inputs and waste emissions (Wijaya et al., 2020; WWF, 2023).

### 2.3. Soil Organic Carbon as an Indicator of Ecosystem Regeneration and Emission Reduction

Soil organic carbon (SOC) is widely regarded as the most integrative indicator of soil health, functioning simultaneously as a measure of nutrient cycling capacity, water retention, aggregate stability, and biological activity (Lal, 2004; Minasny et al., 2017). From a climate perspective, SOC is also a direct proxy for carbon sequestration: each unit of SOC stored represents a unit of atmospheric CO2 that has been removed from circulation through photosynthetic fixation and incorporated into stable soil organic matter pools. The '4 per 1000' initiative, launched at COP21 in Paris, formalised the scientific consensus that a 0.4 percent annual increase in global SOC stocks could halt the rise of atmospheric CO2 concentrations — a goal achievable, at least theoretically, through improved land management (Minasny et al., 2017; Poulton et al., 2018).

Measurement of soil carbon stocks has gained traction as a key proxy for emission reduction, especially in regenerative agriculture frameworks, as soils represent a significant carbon pool capable of sequestering atmospheric $CO_2$ (Besar et al., 2020). By monitoring changes in soil organic carbon (SOC), practitioners can assess progress toward climate mitigation goals and understand the long-term impacts of improved management practices (Toh et al., 2022).

SOC dynamics in tropical agricultural soils are complex and highly variable. In mineral soils under oil palm in Sumatra, baseline SOC concentrations typically range from 1.5 to 3.5 percent in the topsoil (0–30 cm), declining sharply with depth (Dislich et al., 2017; Guillaume et al., 2018). Land use change from forest to oil palm is generally associated with significant SOC losses, particularly in the topsoil, though the magnitude of loss varies with prior land use, soil texture, and management history. Guillaume et al. (2015) found that conversion from jungle rubber to oil palm in Jambi resulted in a 20 to 30 percent reduction in topsoil SOC within the first decade of cultivation, with losses concentrated in the labile, plant-available carbon fractions. However, long-established plantations in their second rotation cycle can partially recover SOC stocks if organic matter inputs are managed carefully, suggesting that SOC trajectories are reversible given appropriate management over sufficient timescales.

## 3. Material and Method

### 3.1. Study Site

Two case studies were used for in depth inquiries. The first was Bandarejo Village, Simalungun Regency, Bandar Masilam Sub District, North Sumatera, where representing a trial area of regenerative agriculture using compost fertilizer. The second was Mekarsari

Village, Rimbo Ulu Sub District, Tebo Regency, Jambi, representing trial area of regenerative agriculture using organic fertilizer from manure and *Oil Palm Empty Bunches* (EFB).

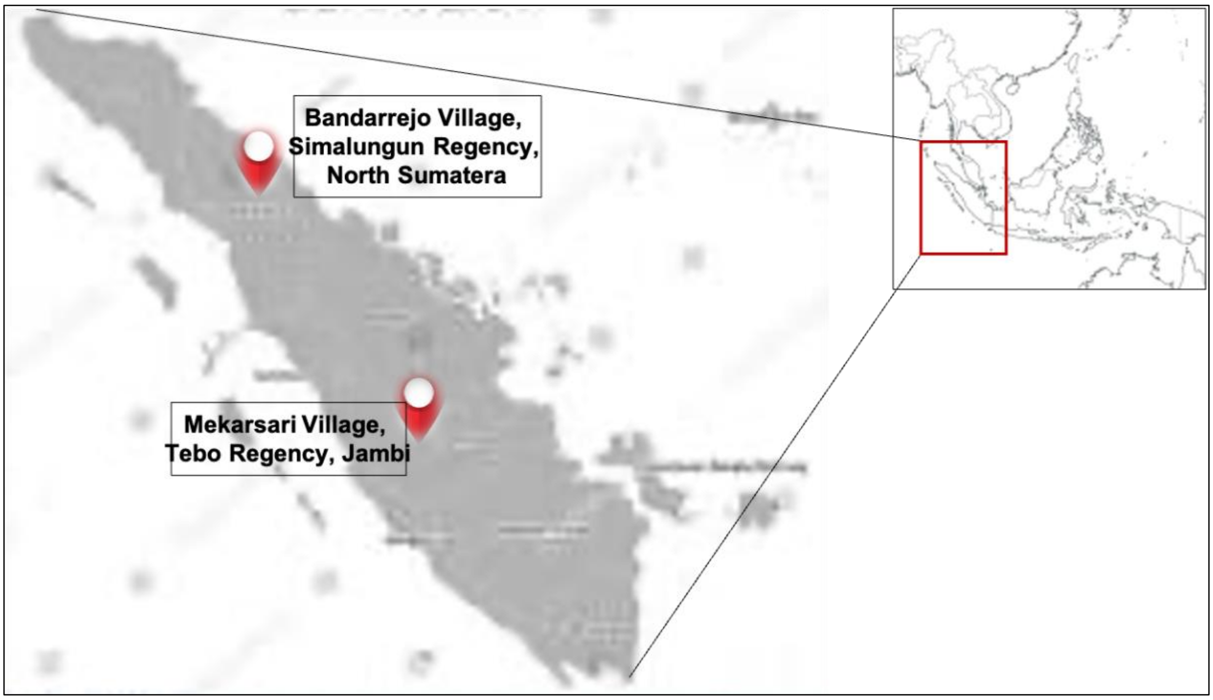


Figure 1. Relative position of the study sites in North Sumatera and Jambi

Initial investigation of SOC in this regenerative agriculture trial area is important to validate the extent to which regenerative agriculture has an impact in the pilot area. Theories in textbooks may not necessarily align with real-world applications. Soil texture, microclimate, local pests, and farmer habits may vary. Pilot testing provides concrete evidence. Secondly, the important initial investigation is to identify the most effective combination of practices, with the ideal composition varying in each location, and to minimize risk before large-scale implementation. Failure in a pilot area results in small losses but provides significant lessons. Meanwhile, large-scale failure results in significant losses and erodes farmer confidence. Testing provides a safe space for mistakes, learning, and improvement before implementing on a larger scale. Additionally, it is important to build evidence for stakeholders, among other, other farmers for replication, donors, or certification auditors, to build the trust.

## 3.2. Examining Soil Organic Carbon (SOC) Performance

***Determining Number of Sampling Plot***

There were two treatment groups at North Sumatera and Jambi study sites: regenerative agriculture and conventional/non-regenerative agriculture as a control. The regenerative agriculture means smallholder oil palm plantations treated by additional organic fertilizer, while the control means smallholder oil palm plantations treated pure chemical fertilizer. Sample plots were built in each treatment group with replications. The distribution of sample plots is presented in Table 1.

Table 1. Number and distribution of the SOC sampling plots

| Site | Treat-ment | Plot no. | Latitude | Longitude | Number of sample point | Number of soil composite |
|---|---|---|---|---|---|---|
| Bandar Rejo Village, Simalungun Regency, North Sumatera | Organic | 1 | 3,279304 | 99,335918 | 5 | 4 |
| | Organic | 2 | 3,279418 | 99,339981 | 5 | 4 |
| | Organic | 3 | 3,279955 | 99,340226 | 5 | 4 |
| | Control | 1 | 3,279619 | 99,336996 | 5 | 4 |
| | Control | 2 | 3,279101 | 99,337077 | 5 | 4 |
| | Control | 3 | 3,279433 | 99,337582 | 5 | 4 |
| | **Total** | **6** | | | **30** | **24** |
| Mekarsari Village, Tebo Regency, Jambi | Manure | 1 | -1,229393 | 102,093967 | 5 | 4 |
| | Manure | 2 | -1,22935 | 102,093632 | 5 | 4 |
| | EFB | 1 | -1,221797 | 102,035236 | 5 | 4 |
| | EFB | 2 | -1,243351 | 102,082358 | 5 | 4 |
| | Control | 1 | -1,217464 | 102,05498 | 5 | 4 |
| | Control | 2 | -1,217208 | 102,054487 | 5 | 4 |
| | **Total** | **6** | | | **30** | **24** |

A square sample plot was selected with dimensions of 20 m X 20 m, referring to the Indonesian National Standard (SNI 7724:2019). Points A, B, C, D, and E indicate the distribution positions for soil sampling (Figure 2).

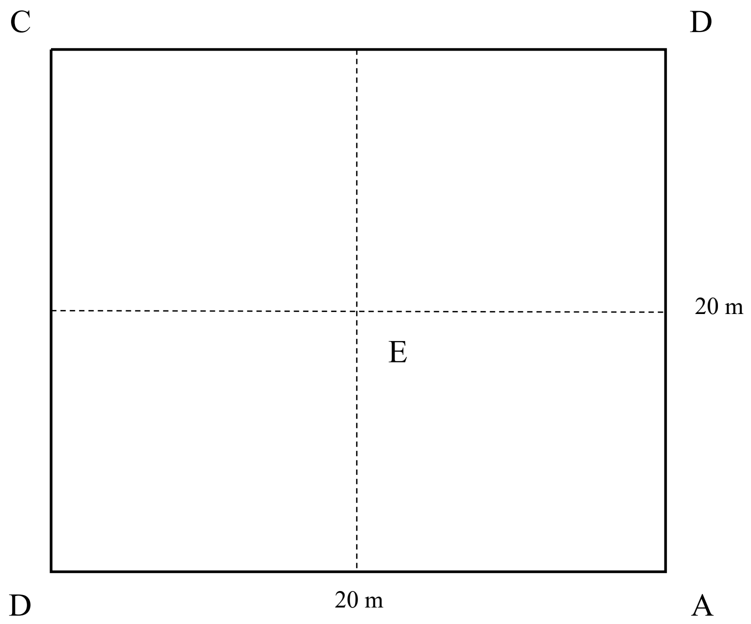


Figure 2. The 20 m x 20 m square plot and the position of soil sample points

***Soil sampling procedure***

Soil sampling was carried out using the following procedures:

- Soil samples were collected in a 20 m x 20 m square plot. Soil sampling points were placed at five points in each plot: at the corners, and the centre.

- At each point, soil samples were taken at four soil depths: 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm.
- At each soil depth, four soil sample rings were implanted (sample ring dimension: diameter of 5 cm and a height of 5 cm).
- The soil samples were then composited for each soil depth (i.e., 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm) and their wet weights were measured. Thus, each sample point provided four composite soil samples.
- For bulk density analysis, one ring of soil sample was taken at each soil depth, at the centre of the plot (point E).
- Soil sample was recorded, including: plot number, location, treatment, replication, sampling point on the sample plot, soil depth, and wet weight, as well as a description of the sample plot.

***Soil samples laboratory analysis***

A total of 120 soil samples were obtained from each study sites (6 plots in total, with 4 soil layers, in each site). This resulted in a total of 240 soil samples from the Jambi and North Sumatra sites, plus 12 samples for bulk density analysis. Further, these soil samples then were performed composite on each plot for each soil layer. There were 24 composite samples were obtained for each study site at the final stage, or 48 composite samples for all locations. The composite soil samples were further sent to the soil laboratory to perform a soil chemical (soil organic C) and soil physical (bulk density) analysis.

***Calculating Soil Organic Carbon (SOC)***

Soil Organic Carbon (SOC) was calculated using the following formula:

***SOC on certain soil layers (tonne/ha) = Bulk Density (gr/cm$^3$) * C Organic (%) * soil thickness (cm) * 100***

***Total SOC (tonne/ha) = ∑SOC on certain soil layers (tonne/ha)***

### 3.3. Examining socio-economic challenges

In this section, the main question that will be answered was what are the social-economic challenges in integrating regenerative farming in their oil palm smallholder practices. Ultimately, it will contribute to emission reduction purpose on beyond sustainability perspective of smallholders' palm oil plantation management.

The socioeconomic data in question includes:

- General information on oil palm cultivation techniques at each study site
- Specific information on organic oil palm plantation management, and
- Smallholder perceptions of organic farming, what are their motivation to implement regenerative farming.
- This study also identified the obstacles that hinder farmers' interest in implementing regenerative farming.

Socio-economic data were collected using in-depth interviews and focus group discussion (FGD) techniques in 25-29 November 2025 and 8-12 December 2025, in North Sumatera and Jambi sites respectively. In-depth interviews were took place to get a deep understanding of smallholder palm oil plantation management both in transition of regenerative and conventional practices.

The representatives of KPUD in Simalungun, North Sumatra, and the PPSRU administrators in Tebo, Jambi, as well as the Setara (a local NGO in Jambi) have been selected as key informants. While the FGD was conducted by inviting key informants representing regenerative farmers and non-regenerative/conventional farmers. A minimum of five key informants were invited for each group. Therefore, the representation of key informants at each location is as follows:

- KPUD Lestari, Simalungun, North Sumatera:
  - Key informants representing conventional farmers: 5 respondents
  - Key informants representing regenerative farmers (compost application): 5 respondents
- PPSU Tebo, Jambi:
  - Key informants representing conventional farmers: 5 respondents
  - Key informants representing regenerative farmers (manure application): 5 respondents
  - Key informants representing regenerative farmers (empty oil palm bunches application): 5 respondents.

## 4. Result

### 4.1. Brief overview of the study sites

***Site 1. Bandarrejo Village, Simalungun Regency, North Sumatera***

Palm oil farmers in Bandarrejo were generally members of the Tol Ramania Farmer Group, with total member of 42 farmers and 36,1 ha of plantation areas. There was 1 farmer has been tried regenerative agriculture in 1 ha of plantation area. The Tol Ramania Farmer Group was affiliated in *the Koperasi Produsen Usaha Dagang* (KPUD) *Lestari*, a village cooperative operated as producers in palm oil trading. Bandarrejo Village was located in Simalungun Regency, North Sumatera Province. There were 945 farmers as member of the KPUD Lestari, with total palm oil plantation area of 1045 ha. Around 50% of them have been applied regenerative farming since 1 year ago. The KPUD secretariate established 6 demo plots regenerative farming application to provide examples of best practices for other farmers.

The initiative of the regenerative farming practices have been started at 2022, by applying compost as an organic fertilizer that consisted of 40% animal manure (cow), 30% boiler ash, and 30% solid waste. Organic fertilizer was applied at 5 kg/oil palm tree as a supplementary fertilizer, while chemical fertilizers are still used. The other treatments of the regenerative farming were mulching by oil palm fronds, as well as zero chemical herbicides and pesticides. However, a chemical fertilizer (NPK) was also applied, using 3 kg/oil palm tree in every 6 months. The soil sampling plots were located in 15-years old palm oil plantation (planted by 2010). It was resulting 300 kg of oil palm fruits for 1 ha (consisted of 100 trees/ha) for harvesting time (every two-weeks).

In general, the soil type formation was identified as Typic Dystrudepts, namely medium-aged volcanic soil, medium fertility level, usually found in flat to undulating areas and in volcanic *lungur* and fan physiography. The average annual rainfall of around 2,779 mm. Monthly rainfall was classified as wet (>100 mm) and was almost evenly distributed throughout the year. The average number of rainy days annually of around 154 days per year and high rainfall intensity usually occur in the wettest months such as May, October to December. Based on the Schmidt & Ferguson climate classification system in 1951, this area is classified as a type A climate (tropical rainy climate).

***Site 2. Mekarsari Village, Tebo Regency, Jambi***

Pal oil farmers in Mekarsari were in majority incorporated in Tunas Lestari Farmer Group, with total member of 155 farmers and 231 ha of plantation area. There were 62 farmers have been tried regenerative agriculture under the 92,40 ha of plantation areas. Tunas Lestari Farmer Group was affiliated in *Perkumpulan Petani Sawit Rimbo Ulu* (PPSRU), a local palm oil farmer association. Mekarsari Village is located in Rimbo Ulu Sub District, Tebo Regency, Jambi Province. There were 1421 farmers as member of the PPSRU, with total palm oil plantation area of 2500 ha. Around 40% the farmers were reported implementing regenerative farming practices (160 of 400 farmers) in the village. The PPSRU secretariate established regenerative farming pilot areas since 2 years ago, applied on 6-7 years old oil palm plantation areas. The initiative of the regenerative farming practices have been started at 2020. There was a regenerative farming training assisted by Will Asia and ICRAF.

Our soil sampling plots were located in 7-years old palm oil plantation. There were 2 types of organic application, namely: oil palm empty bunches (EFB), as well as animal manure and liquid organic matter. EFB application took around 56 tonne per ha. Liquid organic can be created in 1 drum for 200 litter with 3 kg chemical fertilizer. It will be harvested by 3 months resulting 400 litter. The organic application was then mixed with chemical fertilizer (NPK) for every 2 months. Zero herbicides and pesticides were also applied. It was resulting a better productivity after regenerative farming practices, among other 8,5 kg fruits per row plantation (year 1), and 12 kg / row plantation (year 2).

In general, red-yellow podzolic and organosol were the soil types distributed in Rimbo Ulu Sub District. The area has a tropical climate with an average rainfall of 300 mm per year and a humidity level of 56%-85%. The climate was humid tropical with some slight variations in rainfall that are almost evenly distributed throughout the year, while the differences between the dry season (February-August) and the rainy season (September-January) are not very varied.

## 4.2. Impact of regenerative agriculture on SOC-related soil properties

This study focused on two physical and chemical properties of soil that are closely related to SOC, namely: bulk density and C-organic content. All laboratory test results are presented in Table 2.

Table 2. The result of laboratory test for Bulk Density and C-Organic Content in each soil depth in North Sumatera and Jambi sites.

| No | North Sumatera | | | | Jambi | | | |
|---|---|---|---|---|---|---|---|---|
| | Plot Code | Soil depth class (cm) | Bulk Density (g/cm3) | C-Organic (%) | Plot Code | Soil depth class (cm) | Bulk Density (g/cm3) | C-Organic (%) |
| **1** | NS.Organic.P1 | 0-5 | 0,87 | 1,97 | J.Kohe.P1 | 0-5 | 0,93 | 4,07 |
| | | 5-10 | 0,82 | 1,34 | | 5-10 | 1,10 | 2,21 |
| | | 10-20 | 0,86 | 1,11 | | 10-20 | 0,97 | 1,40 |
| | | 20-30 | 0,91 | 1,06 | | 20-30 | 0,86 | 1,19 |
| **2** | NS.Organic.P2 | 0-5 | 1,02 | 0,93 | J.Kohe.P2 | 0-5 | 0,93 | 4,10 |
| | | 5-10 | 0,98 | 1,81 | | 5-10 | 1,00 | 2,41 |

| No | North Sumatera | | | | Jambi | | | |
|---|---|---|---|---|---|---|---|---|
| | Plot Code | Soil depth class (cm) | Bulk Density (g/cm3) | C-Organic (%) | Plot Code | Soil depth class (cm) | Bulk Density (g/cm3) | C-Organic (%) |
| | | 10-20 | 1,13 | 1,42 | | 10-20 | 0,82 | 1,55 |
| | | 20-30 | 1,17 | 1,20 | | 20-30 | 0,74 | 1,21 |
| 3 | NS.Organic.P3 | 0-5 | 1,08 | 2,37 | J.Kimia.P1 | 0-5 | 0,82 | 3,01 |
| | | 5-10 | 1,01 | 1,81 | | 5-10 | 0,92 | 2,24 |
| | | 10-20 | 1,12 | 1,37 | | 10-20 | 0,85 | 1,86 |
| | | 20-30 | 1,09 | 0,90 | | 20-30 | 0,86 | 3,44 |
| 4 | NS.Kimia.P1 | 0-5 | 1,07 | 1,17 | J.Kimia.P2 | 0-5 | 0,81 | 2,66 |
| | | 5-10 | 1,08 | 1,01 | | 5-10 | 0,85 | 4,82 |
| | | 10-20 | 1,02 | 0,90 | | 10-20 | 0,80 | 1,83 |
| | | 20-30 | 1,16 | 0,82 | | 20-30 | 0,92 | 1,65 |
| 5 | NS.Kimia.P2 | 0-5 | 0,86 | 1,44 | J.Tankos.P1 | 0-5 | 0,79 | 3,79 |
| | | 5-10 | 0,88 | 1,05 | | 5-10 | 0,96 | 3,26 |
| | | 10-20 | 0,92 | 2,76 | | 10-20 | 0,89 | 2,79 |
| | | 20-30 | 1,18 | 0,96 | | 20-30 | 1,01 | 1,90 |
| 6 | NS.Kimia.P3 | 0-5 | 1,14 | 1,50 | J.Tankos.P2 | 0-5 | 1,07 | 2,73 |
| | | 5-10 | 1,20 | 1,19 | | 5-10 | 1,06 | 2,64 |
| | | 10-20 | 1,15 | 1,01 | | 10-20 | 1,11 | 2,93 |
| | | 20-30 | 1,13 | 1,04 | | 20-30 | 0,98 | 2,06 |

The key finding from North Sumatera site showed that the results of laboratory test were more positive for the organic treatment in the trial areas of regenerative agriculture. The average of Bulk Density was lower, the average of C-Organic was higher, and the average of SOC was higher than the pure chemical (control). However, the statistical test delivered a not-significantly different of Bulk Density, C-organic, and SOC between transition of the regenerative agriculture and control (Table 3).

Table 3. T-test: Two-sample assuming equal variances of bulk density, C-organic, and SOC between regenerative agriculture trial area and control in North Sumatera

| | Bulk Density | | C-Organic | | SOC | |
|---|---|---|---|---|---|---|
| | *Organik* | *Kimia* | *Organik* | *Kimia* | *Organik* | *Kimia* |
| Mean | 1,005 | 1,065833 | 1,440833 | 1,2375 | 10,3375 | 9,749167 |
| Variance | 0,013845 | 0,014281 | 0,208863 | 0,270693 | 12,75846 | 30,26346 |
| Observations | 12 | 12 | 12 | 12 | 12 | 12 |
| Pooled Variance | 0,014063 | | 0,239778 | | 21,51096 | |
| **Hypothesized Mean Difference** | 0 | | 0 | | 0 | |
| **df** | 22 | | 22 | | 22 | |
| **t Stat** | -1,25653 | | 1,017137 | | 0,31072 | |
| **P(T<=t) one-tail** | 0,111051 | | 0,160072 | | 0,379469 | |
| **t Critical one-tail** | 1,717144 | | 1,717144 | | 1,717144 | |

| | | | |
|---|---|---|---|
| **P(T<=t) two-tail** | 0,222101 | 0,320144 | 0,758938 |
| **t Critical two-tail** | 2,073873 | 2,073873 | 2,073873 |

Slightly different results were shown on the Jambi site. Some key findings indicate that there is a significantly different for Bulk Density between transition of regenerative agriculture and control. Manure and EFB were tends to be denser relatively – the weight of dry soil mass per unit volume is higher than pure chemical treatment. Furthermore, C-Organic and SOC under organic EFB treatment showed higher results than the chemical treatment (control), however, the difference was not statistically significant between two organic treatments (manure and EFB) in regenerative agriculture and pure chemical treatment (control) (Table 4, Table 5, and Table 6).

Table 4. Anova single factor for Bulk Density in Jambi site

SUMMARY

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| J-Kohe | 8 | 7,35 | 0,9188 | 0,0125 |
| J-Tankos | 8 | 7,87 | 0,9838 | 0,0110 |
| J-Kimia | 8 | 6,83 | 0,8538 | 0,0021 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 0,0676 | 2 | 0,0338 | 3,9640 | 0,0346*) | 3,4668 |
| Within Groups | 0,1791 | 21 | 0,0085 | | | |
| Total | 0,2467 | 23 | | | | |

**) significantly different*

Table 5. Anova single factor for C-organic in Jambi site

SUMMARY

| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
|---|---|---|---|---|
| J-Kohe | 8 | 18,14 | 2,2675 | 1,4539 |
| J-Tankos | 8 | 22,1 | 2,7625 | 0,3694 |
| J-Kimia | 8 | 21,51 | 2,6888 | 1,1308 |

ANOVA

| *Source of Variation* | *SS* | *df* | *MS* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| Between Groups | 1,1411 | 2 | 0,5706 | 0,5794 | 0,5689 | 3,4668 |
| Within Groups | 20,6782 | 21 | 0,9847 | | | |
| Total | 21,8193 | 23 | | | | |

Table 6. Anova single factor for SOC in Jambi site

SUMMARY

| Groups | Count | Sum | Average | Variance |
|---|---|---|---|---|
| J-Kohe | 8 | 107,68 | 13,4600 | 13,7744 |
| J-Tankos | 8 | 155,95 | 19,4938 | 41,1595 |
| J-Kimia | 8 | 129,11 | 16,1388 | 40,0313 |

ANOVA

| Source of Variation | SS | df | MS | F | P-value | F crit |
|---|---|---|---|---|---|---|
| Between Groups | 146,2343 | 2 | 73,1172 | 2,3098 | 0,1240 | 3,4668 |
| Within Groups | 664,7569 | 21 | 31,6551 | | | |
| Total | 810,9912 | 23 | | | | |

When looking at the comparison between the 2 separate treatments, another insight was found. There were not-significantly different of SOC between manure organic treatment with pure chemical treatment (control), nor between EFB organic treatment with pure chemical treatment (control). However, a significantly different was shown in SOC between manure with EFB organic treatments, where EFB organic treatment was better than manure organic treatment (Table 7).

Table 7. T-test: two-sample assuming equal variances in SOC between transition of regenerative agriculture and control in Jambi site

| | *J-Kohe* | *J-Kimia* | *J-Tankos* | *J-Kimia* | *J-Kohe* | *J-Tankos* |
|---|---|---|---|---|---|---|
| Mean | 13,46 | 16,13875 | 19,49375 | 16,13875 | 13,46 | 19,49375 |
| Variance | 13,77443 | 40,0313 | 41,15954 | 40,0313 | 13,77443 | 41,15954 |
| Observations | 8 | 8 | 8 | 8 | 8 | 8 |
| Pooled Variance | 26,90286 | | 40,59542 | | 27,46698 | |
| **Hypothesized Mean Difference** | 0 | | 0 | | 0 | |
| **df** | 14 | | 14 | | 14 | |
| **t Stat** | -1,03291 | | 1,053135 | | -2,30256 | |
| **P(T<=t) one-tail** | 0,15958 | | 0,155058 | | 0,018585 | |
| **t Critical one-tail** | 1,76131 | | 1,76131 | | 1,76131 | |
| **P(T<=t) two-tail** | 0,31916 | | 0,310117 | | 0,037169*) | |
| **t Critical two-tail** | 2,144787 | | 2,144787 | | 2,144787 | |

**) significantly different*

Similarly, no significant differences also occurred in each layer of soil depth in the aggregate study sites, both in terms of the effect on bulk density and C-organic content. The deeper the soil layer tends to show the higher the bulk density (Figure 3). Although the bulk density of the soil in the control was slightly looser than that in the organic treatment, this could be due to other factors, such as the level of soil degradation in the previous period or mechanical factors such as livestock grazing activities. On the other hand, the c-organic content in soil with organic treatment was slightly higher than that in the control, and it showed a tendency towards the deeper soil layers. the lower the C-organic content (Figure 4). Additionally, in aggregate soil depth and study sites, the values of bulk density, C-organic content, and SOC showed slightly higher in the organic treatment compared to the control (Figure 5).

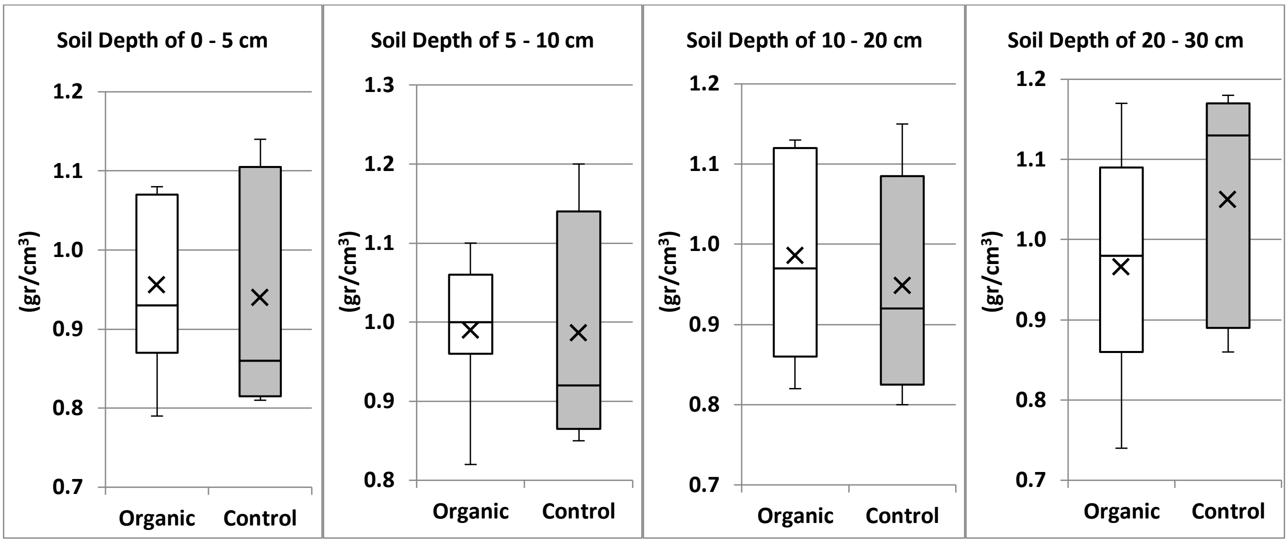


Figure 3. Effect of regenerative agriculture on soil bulk density in various layers of soil depth in North Sumatera and Jambi sites

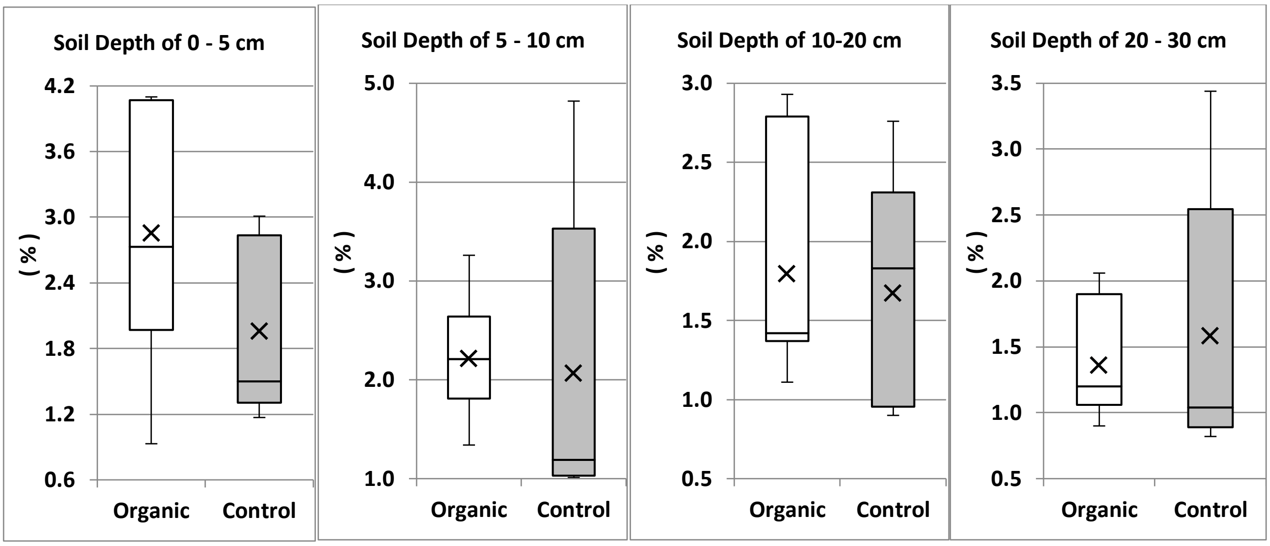


Figure 4. Effect of regenerative agriculture on soil C-organic content in various layers of soil depth in North Sumatera and Jambi sites

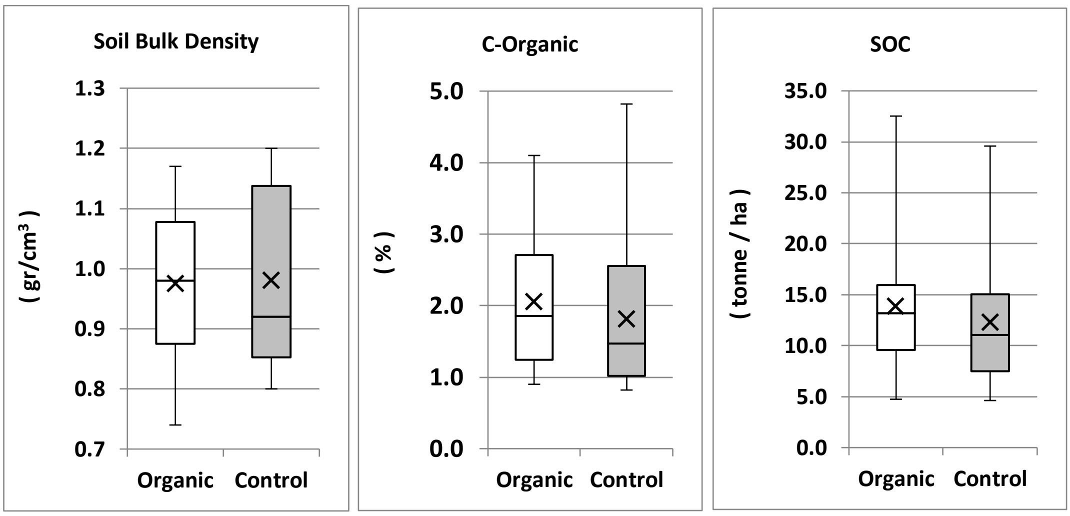

Figure 5. Effect of regenerative agriculture on soil Bulk Density, C-organic content, and SOC in aggregate soil depth and study sites

### 4.3. SOC performance

In the context of SOC performance, a carbon accounting result shown a positive result for regenerative agriculture practices. The study found SOC in regenerative agriculture trial area was higher than pure chemical treatment (control) both for North Sumatera and Jambi sites. Enhancement of SOC were 6,03% for North Sumatera site, and 2,09% for Jambi site due to organic applications as regenerative agriculture practices (Table 8).

Table 8. SOC performance of the regenerative agriculture in North Sumatera and Jambi sites

| No | Site | Plot Code | SOC per Plot (ton/ha) | Average SOC (ton/ha) |
|---|---|---|---|---|
| 1 | North Sumatera | S.Organic.P1 | 33,26 | 41,35 |
| 2 | | S.Organic.P2 | 43,70 | |
| 3 | | S.Organic.P3 | 47,09 | |
| 4 | | S.Kimia.P1 | 30,41 | 39,00 |
| 5 | | S.Kimia.P2 | 47,53 | |
| 6 | | S.Kimia.P3 | 39,06 | |
| 7 | Jambi | J.Kohe.P1 | 54,89 | 65,91 |
| 8 | | J.Kohe.P2 | 52,78 | |
| 9 | | J.Tankos.P1 | 74,64 | |
| 10 | | J.Tankos.P2 | 81,31 | |
| 11 | | J.Kimia.P1 | 68,04 | 64,56 |
| 12 | | J.Kimia.P2 | 61,08 | |

### 4.4. Social economic opportunities and challenges

Interesting results from the perspective of farmers, both farmers who apply organic and conventional treatments, indicated the emergence of opportunities and challenges in the application of regenerative agriculture in oil palm plantation management by smallholders. Farmers in both study sites had positive and negative views towards the application of the regenerative agricultural transition, as shown in Table 9.

Table 9. Pros and cons on transition of regenerative agriculture according to farmers perspective

| Site | Pros | Cons | Other expectations |
|---|---|---|---|
| North Sumatera | • Utilizing compost allocations from cooperative units<br>• Materials are readily available and easy to obtain; compost can be made yourself<br>• Organic fertilizer is cheaper than chemical fertilizers | • Organic fertilizers are suspected to be the cause of Ganoderma on oil palm trunks.<br>• The growth response is slower than chemical fertilizers, requiring 3 months to see results. | Provision of goat livestock assistance for farmers so that farmers can implement a circular economy |

| Site | Pros | Cons | Other expectations |
|---|---|---|---|
| | • Good for fruit production and greener leaves<br>• Looser soil, rich in worms and other soil organisms | | |
| Jambi | • Organic treatment generates greener and fresher leaves.<br>• Improving soil nutrients<br>• Farmers have raw materials for making organic fertilizer, such as manure.<br>• Our soil will be better protected. The soil nutrients will be maintained during replanting time. | • The type and quality of seeds are the main factors influencing oil palm productivity. The use of organic fertilizers does not necessarily result in more fruit.<br>• The material of organic fertilizer was difficult to obtain.<br>• The production process of organic fertilizer requires more time. | • Chemical fertilizers will have to be reduced in the future.<br>• Farmers want to see first what the results of organic applications are. |

In general, oil palm farmers have not been fully understood the importance and benefits of regenerative agriculture on soil, and its implications for oil palm health and growth. However, for more sustainable oil palm plantation management in the future, they have positive expectation for plantation management improvement, although empirical evidence as a pilot area is needed for the real example of best practices.

## 5. Discussion

This study has been produced several important insights in supporting theoretical and practical significances. We focused on four main insights, including: the strength of regenerative agriculture towards new sustainability, insignificant impacts on SOC-related soil properties due to insufficient application, SOC enhancement offers a positive climate-mitigation contributions, and managing social barriers and opportunities.

### 5.1. The strength of regenerative agriculture towards new sustainability

Farmers have begun implementing regenerative agriculture through the application of organic fertilizers. Therefore, this study promotes the concept of regenerative agriculture toward new sustainability, though its definition remains contested and its theoretical foundations eclectic. Regenerative approaches share a common orientation toward restoring ecological function rather than merely sustaining existing production levels (Rhodes, 2017; Newton et al., 2020). Core principles typically include minimising soil disturbance, and maintaining continuous soil cover to restore landscape ecology.

Knowledge and awareness on regenerative agriculture for soil sustainability have been a mainstream among farmers, although not yet evenly distributed among all farmers in the study sites. Nevertheless, this has set a positive outcome for the development of more sustainable oil palm plantation management by smallholders.

In oil palm landscapes, the circularity of nutrient flows is particularly relevant: empty fruit bunches (EFBs), and other palm oil mill effluent represent significant organic nutrient resources that, when returned to plantations, can partially substitute for synthetic fertilizers and enhance SOC stocks. Studies by Corley and Tinker (2016) demonstrated that systematic EFB application can increase soil organic matter content by 20 to 40 percent over a five-year period, though effects are highly site- and management-specific. The articulation of these practices within an explicit circular economy narrative offers corporate buyers and smallholder programs a coherent framing for regenerative value chains.

The application of regenerative principles to permanent monocrop systems such as oil palm presents both opportunities and conceptual challenges. Unlike annual cropping systems, oil palm has a productive lifespan of 25 to 30 years and occupies a relatively stable canopy structure, which creates distinctive conditions for soil carbon dynamics and under-canopy biodiversity management. Chiu and Mahendrappa (2020) argued that regenerative practices in oil palm landscapes can meaningfully contribute to soil organic matter accumulation. However, it's acknowledged that converting conventional practices to full regenerative agriculture is highly challenging. A high intensity and quantity of organic fertilizer are required to completely replace chemical fertilizers for oil palm productivity.

### 5.2. Insignificant impacts on SOC-related soil properties due to insufficient application

Insignificant impacts on SOC-related soil properties (such as bulk density, and C-organic content) is highly related to insufficient quantity and quality of the organic application. Those organic applications were the trial practices dedicated by farmers, that is currently in the first and the second years. Furthermore, organic fertilizer is considered as a supplementary measure, while chemical fertilizers remain intact. The use of chemical fertilizers to ensure fruit productivity is a primary argument for farmers. Organic fertilizers alone may not provide sufficient nutrients to meet the high demands of oil palm trees, especially during the production phase. This can result in nutrient deficiencies, reduced growth, and lower yields, which are already a significant issue in smallholder plantations (Lim et al, 2023; Woittiez et al, 2018). The use of a long time and intensive chemical fertilizer can affect the effectiveness of organic treatment.

Organic fertilizers can improve soil organic carbon and yields, but their benefits are site-specific and depend on proper application. Without targeted management, nutrient depletion and soil degradation can still occur, threatening long-term sustainability (Essono et al, 2023; Rudolf et al, 2021). High-density planting and poor conservation practices further reduce the effectiveness of organic fertilizers by increasing competition for limited nutrients (Essono et al, 2023). Quezada et al (2019) also reported that C-organic content in the soil down to 50 cm constantly decreased until the beginning of the second oil palm cycle, after which C-organic stabilized along the second rotation.

SOC changes in response to management interventions operate on multi-year to decadal timescales, often with high inter-annual variability driven by rainfall, temperature, and crop growth cycles (Smith, 2004). This temporal inertia means that short-term measurement campaigns — of the kind feasible within project or program evaluation windows — are unlikely to detect statistically significant SOC changes against background variability, unless supported by robust baseline data, large sample sizes, and rigorous spatial stratification (Conant et al., 2011). These limitations have been extensively discussed in the context of voluntary carbon markets, where the permanence and additionality of soil carbon credits remain active areas of debate (Oldfield et al., 2022; Cacho et al., 2005).

The effectiveness of SOC-enhancing practices depends on factors such as soil type, plantation age, and management intensity (Nairot et al, 2022; Rahman et al, 2021). Spatial heterogeneity in soil properties, variations in plantation age, and differences in management intensity complicate sampling design and data interpretation are the other factors influencing the effectiveness of regenerative practices on the SOC performance (Toh et al., 2022).

### 5.3. SOC enhancement offers a positive climate mitigation contribution

Although the increased SOC in this study ranged from 2–6%, it indicates a positive contribution to climate mitigation efforts. Conceivably, an increase of 1.35 to 2.35 tonne of SOC/ha contributes to emission reductions equivalent to 4.94 tonne of $CO_2$/ha to 8.62 tonne of $CO_2$/ha compare with and without regenerative agriculture. If the regenerative practices are implemented on a large-scale plantation area, the cumulative emission reductions would be significant. This would also emphasize the role of smallholder oil palm plantations, in particular, in reducing the carbon footprint, at least at the plantation stage. The emission reductions in the agricultural sector have not yet reached the application of regenerative farming in plantations sub sector, where the government's focus only on the rice fields and livestock sub-sectors.

The effectiveness of regenerative agriculture varied depending on the frequency and rate of organic application. This is inline with Nairot et al, (2022) who reported that the long-term organic application (e.g. 21 years) showed heterogeneous, but positive effects on SOC, with significant carbon sequestration in specific plantation zones (e.g. harvesting paths). Another scholar also reported that applying EFB as mulch in smallholder oil palm plantations increased SOC by 19% compared to non-mulched areas. This practice also improved soil chemical functions, such as cation exchange capacity, and enhanced nutrient availability (e.g. potassium and magnesium) (Rudolf et al, 2021).

### 5.4. Managing social barriers and opportunities

Regenerative agriculture is then considered a promising strategy for improving SOC. However its widespread adoption is limited by several factors. Observing the socio-economic challenges and opportunities in implementing regenerative agriculture on smallholders oil palm plantations management, it leads to the important of managing social barrier and take advantage of opportunities.

Limited resources availability is one of the significant barriers (Rudolf et al, 2021; Nairot et al, 2022). Smallholders of oil palm plantations often facing limited resources, such as capital, technology, and knowledge, to implement regenerative agricultural practices. Therefore, encouraging the increased adoption of technology by awareness raising, and knowledge transfer should be a main concern. Organic fertilizers, such as compost or empty fruit bunch (EFB) mulch, are not always available in sufficient quantities. Regional supply constraints and logistical issues limit their widespread application (Woittiez et al, 2018b; Rudolf et al, 2021).

Additional costs are required for the implementation of regenerative agriculture, making it difficult for smallholders of oil palm plantations to implement these practices. Smallholders often face financial limitations, which restrict their ability to purchase sufficient quantities of fertilizers, including organic options (Lim et al, 2021; de Vos et al, 2026). Access to credit is a critical enabler, farmers with credit access tend to use more fertilizers and achieve better nutrient scores (de Vos et al, 2026).

Subsidies and support programs often favor inorganic fertilizers, leaving organic options underutilized. Additionally, certification schemes like ISPO have shown potential to improve resource use efficiency but are not yet widely adopted (Liana et al, 2025). The existence of a strong and consistent institutions (such as cooperatives, and farmer associations) in mainstreaming organic applications in the application of regenerative agriculture will be an important agent for the success of the implementation.

Those social barriers and opportunities are important to be understood. Based on that, future directions can be addressed through developing strategies to assist smallholder oil palm plantations in implementing better regenerative agricultural practices.

## 6. Concluding Remarks: Implication for smallholder regenerative farming framework

The study concludes in two important contexts, namely what are the implications for smallholder oil palm plantation management, and claim the study limitation to propose the future research direction.

### *Implications for smallholder oil palm plantation management*

As a conclusion, the following points deliver a couple of implications for smallholder regenerative agriculture framework, namely:

- Increasing technology adoption: Providing education and training to smallholders on regenerative farming techniques, including their benefits for soil and oil palm productivity, needs to be provided intensively and regularly, using innovative learning media.
- Access to organic materials: Providing smallholders with access to organic resources, including the use of local organic materials to reduce dependence on external inputs, will help them increase organic use and independent organic production.
- Collaboration and networking: Building collaboration and networks between smallholders, the governments, and industries to improve market security for organic palm oil products and ensure a sufficient and sustainable supply of raw materials.
- Developing an incentive and reward system: Providing incentives and rewards to smallholders who successfully implement regenerative agriculture practices, such as recognition and prizes, are highly important pathways to encourage farmers motivation in applying regenerative agriculture.

By implementing these improvements, smallholders can increase production and income, improve soil and environmental quality, and ultimately resulting in an improved smallholder regenerative agriculture framework.

### *Study limitations and future research direction*

This study is limited in farmer groups with transition of regenerative agriculture or trials model of regenerative agriculture practices. Therefore, a comparative study with regenerative agriculture success stories is crucial to provide stronger empirical evidences. This study also limits the analysis to the impact of regenerative agriculture on soil fertility and health, while farmers' needs begin with a desire to understand its impact on soil fertility and soil health to ensure oil palm productivity. Therefore, research on the impact of regenerative agriculture on soil fertility and soil health is urgently needed. In addition, the study also does not discuss the social engineering necessary to increase the success of mainstreaming regenerative agriculture. These social engineering strategies are also important, and future research should consider this aspect.

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